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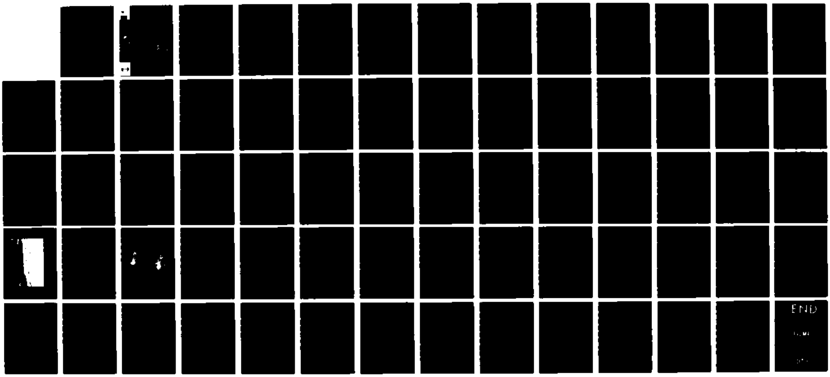

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TRANSPLANTING OF THE SEAGRASSES *ZOSTERA MARINA* AND *HALODULE WRIGHTII* FOR SEDIMENT STABILIZATION AND HABITAT DEVELOPMENT ON THE EAST COAST OF THE UNITED STATES

by

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There is little information on procedures for evaluating potential eelgrass *(Z. marina)* and shoalgrass *(H. wrightii)* planting sites. One major reason for the sparcity of information is that some critical environmental factors controlling eelgrass and shoalgrass growth are poorly documented for transplanting conditions. Study sites were selected which represent a wide range of environmental conditions under which eelgrass and shoalgrass locally occur. The environmental factors considered were temperature, salinity, (Continued)

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light and depth, sediment characteristics, and hydraulic regime. Local temperature and salinity ranges were stenotypic across the sites, but light and depth and hydraulic regimes (which control sediment characteristics) displayed wide variations and had intrinsic control over the distribution of these two seagrasses. Annual temperature and salinity for all sites ranged from 9° to 29° C and 24 to 36 parts per thousand, respectively. Light and depth interactions produced light energy variations from 1.2 to 36 percent of incident photosynthetically active radiation. The hydraulic regimes of the study were described by currents ranging between sites from 2.5 to 92.0 cm/sec and sediment height changes up to 0.6 cm/day (50-day average).

At sites which meet evaluation criteria, the mean vegetative growth rate of transplanted seagrass can be predicted. Actual on-site vegetative growth rates can vary from this mean by 25-50 percent because of local environmental conditions. Vegetative recovery of appropriate sites can be accelerated dramatically by use of eelgrass and shoalgrass transplanting techniques, often by time measured in years.

Site design guidelines for sediment stabilization concentrate on placing nonchemically polluted material at an appropriate depth while maintaining the physical integrity of the site. Semienclosed embayments protected from prevailing winds are suggested as preferred planting sites. Unconsolidated sediments may be protected by artificial wave-dampening devices until seagrass transplants coalesce, as well as by conjunctive planting with other plant species across adjacent intertidal habitat.

Transplant stocks for either species should consist of mature, vegetative shoots with rhizomes collected from high-current areas. Shoalgrass stock should have a high percentage of terminal meristems. Bundles of shoots are attached to anchors and planted. Equations are given for determining amount of transplant stock and spacing required to cover sites in a specified number of days. About 614 man-hours are required per acre of bottom planted, although this value may be considerably lower for some environments. Planting may be done by wading or SCUBA-assisted workers depending on water depth.

The major value of seagrasses in sedimentary dynamics is stabilization, rather than accretion of sediments. In most natural seagrass meadows, sedimentary accretion appears to be balanced by erosion.

PREFACE

This report was sponsored by the Office, Chief of Engineers (OCE), US Army, as a part of the Environmental Impact Research Program (EIRP) Work Unit 31632 entitled Coastal Engineering Uses of Vegetation, which was assigned to the US Army Coastal Engineering Research Center (CERC). The Center, originally located at Fort Belvoir, Va., moved to the US Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss., on 1 July 1983. The Technical Monitors for the study were Dr. John Bushman and Mr. Earl Eiker of OCE and Mr. David B. Mathis, Water Resources Support Center.

The study and preparation of a draft final report were accomplished during the time period 1 October 1982 to 1 October 1983; preparation of the reproducible copy was done during February 1984.

The report was prepared by M. S. Fonseca, W. J. Kenworthy, G. W. Thayer, D. Y. Heller, and Kathleen M. Cheap of the Southeast Fisheries Center, Beaufort Laboratory, Division of Estuarine and Coastal Ecology, National Marine Fisheries Service, under Support Agreement CERC 81-40 W74-RDV.

The authors gratefully acknowledge the following scientists who helped during various aspects of this study: D. Coble, Dr. D. Colby, T. Currin, H. Gordy, Dr. J. Homziak, Dr. B. Kirby-Smith, M. LaCroix, L. Phillips, Dr. R. Phillips, M. Robertson, H. Stuart, and the staff of Mangrove Systems, Inc. Mr. Fonseca's participation in this research was made possible through an Intergovernmental Personnel Agreement between the University of Virginia and the National Marine Fisheries Service. Dr. J. C. Zieman of the University is gratefully acknowledged for sponsoring this agreement.

Mr. Paul L. Knutson, Coastal Ecology Branch, was the CERC contract monitor for the research, under the general supervision of Mr. E. J. Pullen, Chief, Coastal Ecology Branch, and Mr. R. P. Savage, Chief, Research Divison. Dr. Roger T. Saucier, WES, was the Program Manager of EIRP.

Technical Director of CERC at Fort Belvoir during the study and preparation of the draft final report was Dr. Robert W. Whalin. Commanders and Directors of WES during preparation of the reproducible copy and review for publication were COL Tilford C. Creel, CE, and COL Robert C. Lee, CE; Technical Director was Mr. F. R. Brown. Director of WES during publication of this report was COL Allen F. Grum, USA, and Technical Director was Dr. Whalin.

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CONTENTS

TRANSPLANTING OF THE SEAGRASSES *Zostera marina* and *Halodule wrightii* FOR SEDIMENT STABILIZATION AND HABITAT DEVELOPMENT ON THE EAST COAST OF THE UNITED STATES

PART I. INTRODUCTION

1. In May 1981, the National Marine Fisheries Service (NMFS), Southeast Fisheries Center, Beaufort Laboratory initiated a study with the US Army Corps of Engineers, Coastal Engineering Research Center (CERC), on the transplanting of seagrasses.

2. The objectives of the study were as follows:

   a. Perform feasibility evaluations of (eelgrass) *Zostera marina* and (shoalgrass) *Halodule wrightii* transplants including recommendations on specific site evaluation procedures, techniques, and cost projections;

   b. Describe and quantify the influence of natural and transplanted eelgrass and shoalgrass meadows on current reduction and wave dampening for the purpose of sediment stabilization;

   c. Use information from a and b to delineate engineering and planting procedures for both eelgrass and shoalgrass in temperate waters to promote sediment stability and biological habitat development.

3. This report summarizes site evaluation procedures, transplanting methodology, and cost evaluation, as well as preliminary sediment stabilization data resulting from this research.

4. Little information exists on procedures for evaluating potential seagrass planting sites. Critical environmental factors controlling eelgrass and shoalgrass growth are poorly documented for transplanting conditions, and when these factors have been documented, measuring them on a "case-by-case" basis to determine the suitability of potential planting sites often requires expensive equipment and highly trained personnel. A further objective of this report is to create reliable instructions and planting guidelines requiring a minimum of technical background and support based on extensive experimentation, field surveys, and practical experience.

PART II. ENVIRONMENTAL PARAMETERS: STUDY SITES

Location and Dimensions

5. All study sites were located in Carteret County, North Carolina, and were chosen to represent the range of habitat types in which eelgrass and shoalgrass occur in a local coastal plain estuary. Planting sites and planting material collection sites were classified as either high or low current areas. This differentiation was based on whether maximum current velocities were greater or less than 50 cm/sec (Fonseca et al. 1983). Some sites were deliberately selected in extremes of the plant's distribution, either in terms of current velocities and shifting sediment or light limitation and exposure (desiccation). The environmental data collected at these sites provided quantitative boundaries of environmental conditions within which the suitability of a planting site could be determined. Our methods are briefly described in this part under each data type described below. Experimental transplant dimensions are described in Table 1. The site locations are cross-referenced with Figure 1.

Bathymetry

6. Bathymetry of all intensively studied transplant sites was surveyed relative to mean sea level (MSL) (Table 2). These measures were obtained independently and cross-checked through the use of several widely dispersed US Army Corps of Engineers and Geodetic Survey benchmarks as survey points. Standard survey equipment and recent benchmarks (surveyed no earlier than July 1980) were used.

Sediment Characteristics

7. Surface sediments were sampled seasonally at all transplant sites using 6.3-cm-diam lexan tubes. Two cores were collected from each site during each sampling time. The tubes were pushed approximately 25 cm into the sediment, capped at the top, extracted, capped at the bottom, and transported upright to the laboratory to minimize disturbance of the sediment profile. Cores were frozen until analysis. When thawed, the top 1 cm of sediment was carefully extracted for analysis.

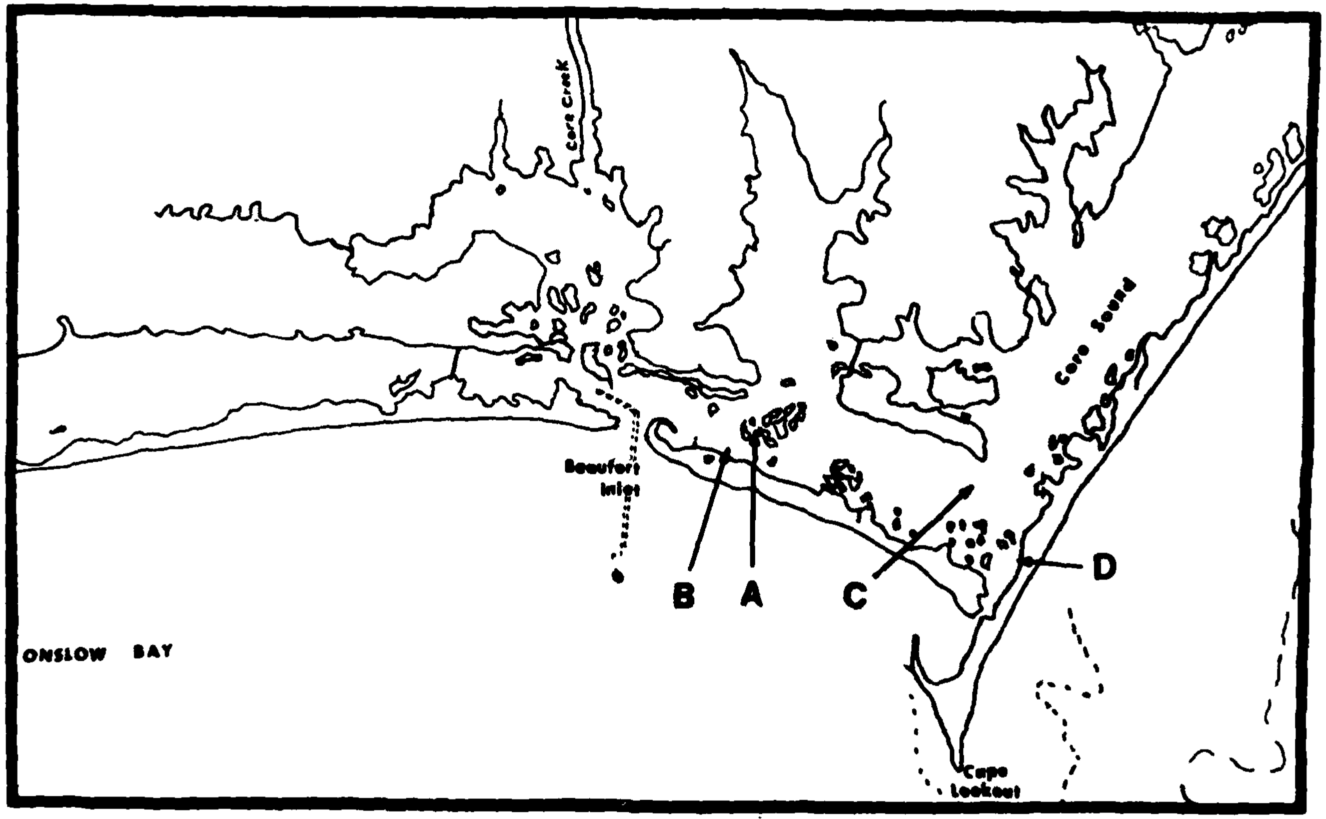

Figure 1. Location of major study sites in Back Sound, Carteret County, North Carolina. Location A = Middle Marsh Embayment; B = Shackleford Shoal; C = Dredged Material Island (shallow and deep sites); D = Barden Inlet. Location letters are cross-referenced with Table 1.

8. The 1-cm sediment slices were placed in a drying oven at 90^{o}C and allowed to dry to a constant weight. After drying, each sample was pulverized in an electric pulverizer for 20 min to ensure that particles consolidated by the drying process were disaggregated. Samples then were sieved in a sediment shaker for a 20-min period, using sieve mesh sizes of 2.00 mm, 1.00 mm, 0.5 mm, 0.25 mm, 0.125 mm, and 0.063 mm. Contents of each sieve were weighed to the nearest 0.0001 g. Particle-size distributions in each sample were characterized using the phi notations of Inman (1952). Phi mean, phi deviation, skewness, and kurtosis were calculated by statistical techniques of Folk and Ward (1957). Two subsamples were obtained from each sample, with percent organic matter of each determined by combustion at 500^{o}C for 24 hr.

9. The results of the sediment survey are presented in Table 3. Only sites where planting units persisted are discussed in order to relate growth to habitat type. Sand fractions of the sediments were medium to fine (Wentworth scale) corresponding to 0.25-0.125 mm nominal diameter. Sorting coefficients (Folk and Ward 1957) describe the sediment of all sites as being moderately sorted (moderate standard deviation of particle sizes). The Dredged Material Island sites displayed a wide range of skewness values, from complete negative (coarse-tending) to positive (fine-tending) skewness (Folk and Ward 1957). The range was greater in the shallower, more wave-influenced Dredged Material Island site. Middle Marsh Embayment displayed a generally positive skewness, which supports other sediment parameters depicting the fine sediments found in that site. Shackleford Shoal had a nearly symmetrical particle size distribution around the medium sand size. Kurtosis measurements range from mesokurtic to very leptokurtic for all sites with broad variation found over time within a given site. The kurtosis measurements generally agree with the sorting coefficients.

10. Except for one location in the Dredged Material Island deep site, the sites may be characterized as ranging from relatively high to low percent organic matter and percent silt-clay as follows: Middle Marsh Embayment, Dredged Material Island (deep), Dredged Material Island (shallow), and Shackleford Shoal. Percent organic matter and percent silt-clay were positively correlated ($r^2 = 0.78$). Sediment characteristics for sites

planted in 1978 (Middle Marsh Embayment) and 1979 (Shackleford Shoal) are not measurably different (Kenworthy et al. 1980; Kenworthy 1981; Fonseca et al. 1983; and Fonseca, unpublished data) indicating that these areas have had similar rates of sediment deposition over recent years. The high values recorded on November 19, 1981 at the Dredged Material Island deep site were likely from terrigenous sources. A strong northeast wind (+ 15 m/sec) and several centimeters of rain on the previous day resulted in the deposition of several millimeters of silt and organic matter on local channel bottoms. This sediment was dispersed within a week following the storm event.

Flowmeter Readings

11. Current velocities for each habitat (each of which may have several adjacent planting sites) were measured by two propeller-type flowmeters read over a tidal cycle. Readings were taken approximately every 15 min, and the maximum velocity was taken to characterize the habitat. All velocities were corrected to the approximate value achieved at a station during the maximum velocity attained during a lunar cycle (based on the National Oceanic and Atmospheric Administration Tidal Current Tables for 1981). This correction was performed to normalize the effect a current has in a given habitat on sediment distribution in the seagrass beds. The sites from low to high current velocities are: Middle Marsh Embayment (2.4 cm/sec); Bigfoot Slough (11.0 cm/sec); Dredged Material Island (16.5 cm/sec), Barden Inlet (36.0 cm/sec); and Shackleford Shoal (92.0 cm/sec).

Temperature and Salinity

12. Seawater temperatures were recorded as daily highs and lows at Duke Marine Laboratory. Average daily temperature and mean monthly values with grand means from all months for the study period were computed (Table 4). Salinity measurements (same station) were available for January-August 1982. The range was 23.6 - 35.9 ppt (parts per thousand) with an 8-month average of 27.6 ppt.

13. All surviving study sites were within 13 km of the temperature/ salinity station at Duke Marine Laboratory; most were within 4 km. Onsite observations indicate that temperatures in Middle Marsh

Embayment ranged 3-5^{o}C higher and lower than the Duke Marine Lab Station in the summer and winter, respectively. Water exchange is relatively limited at the Middle Marsh Embayment location; thus, more extreme changes in temperature could occur there than at the other sites, which are influenced by the latent heat reservoir of a larger water mass.

Light

14. Data on transmission of light through the water column were recorded over a 12-month period. One arbitrarily selected high and low tide was sampled at each site each week. A Sea Tech 25-cm transmissometer was used to measure light transmission. Data were recorded as attentuation coefficients k for each site. The values of k for 1981-82 are shown in Figure 2. Except for a consistent increase in water clarity over the winter, no strong seasonal pattern of k was evident. Fluctuations in k are strongly controlled by local wind and rainfall conditions. The nature of these wind and rain events are generally stochastic, and no coherent pattern of k as a result of wind and rain is evident on the time scale sampled. Therefore, data were reduced to average yearly values.

15. To compare the planting sites on a light energy basis, average depth z relative to mean sea level MSL , and average yearly attenuation k were used in the following equation:

$$I_{(z)} = I_{(o)}e^{-kz} \qquad (1)$$

where: $I_{(z)}$ = light at depth (z)

$I_{(o)}$ = incident light at sea surface

Given that $I_{(o)}$ = indicated photosynthetically active radiation (PAR), the value determined by e^{-kz} (a value between 0 and 1.0) is a factor by which incident light is reduced as a function of attenuation and depth. Also, given that incident light is equal at all of the surviving sites (7 km maximum distance between), the value $e^{-kz} \times 100$ is estimated to be the average percentage of incident light available at the sediment surface of each site yearly (Table 2).

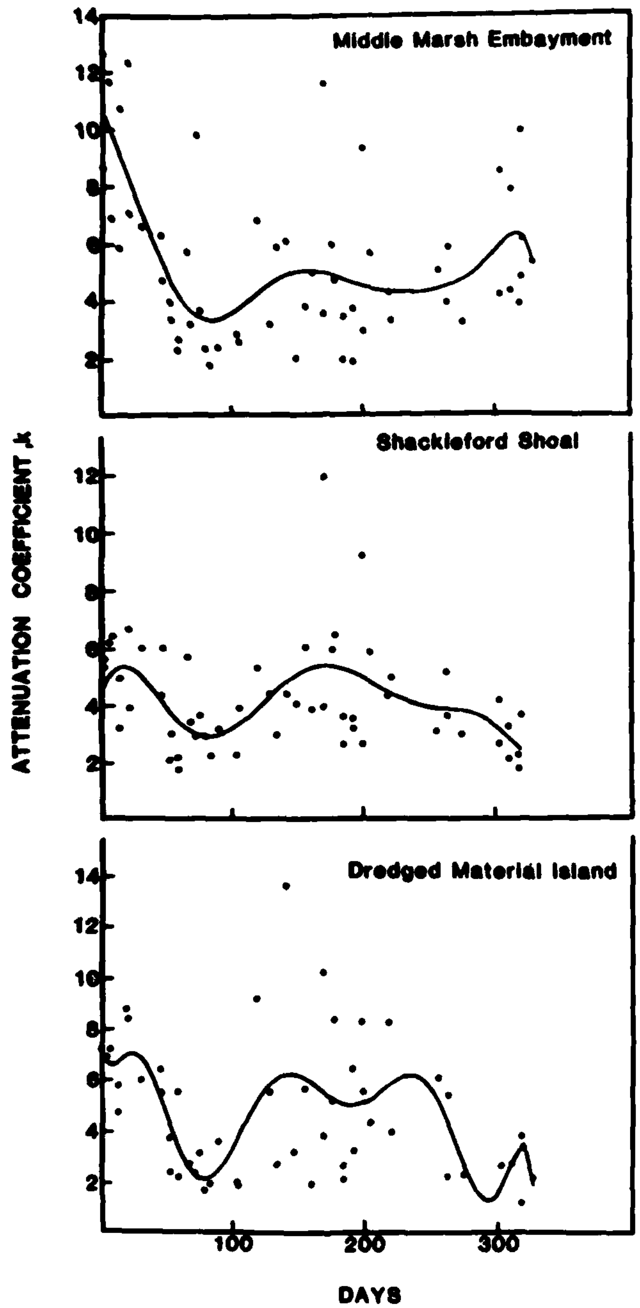

Figure 2. Attenuation coefficients k for all major sites listed in Figure 1 for one arbitrarily selected incoming and one outgoing tide per week for 1 year. Day 1 = September 19, 1981. Lines are N-degree polynomial regressions intended to illustrate possible trends in light levels over the year.

Sediment Flux Rate

16. All six shoalgrass planting sites and three eelgrass sites were surveyed relative to a common datum at each site at least once every 7 days to determine the rate at which the sediment surface accreted and eroded over time. These changes are referred to as the "sediment flux rate" (SFR). Elevational measurements were taken of the sediment surface relative to datums at each site, and flux rate was represented as the value of gross changes in sediment elevation reduced to an average per day basis. The surveys were performed only for a 50- to 60-day period after planting, since actual rooting of the planting units after this time period exerts an effect on sediment stability.

17. The flux rates for six planting sites are given in Table 5. Values are given for transplant sites that survived beyond the second population survey. One exception is the Barden Inlet site, which did not survive. The sites ranged from highest to lowest flux rate as follows: Barden Inlet; Shackleford Shoal, eelgrass and east half of the shoalgrass site; Shackleford Shoal, west half of the shoalgrass site; Dredged Material Island and Middle Marsh Embayment. The flux rate is strongly related to the current regimes of the sites.

Population Dynamics

18. The natural recruitment of eelgrass in three representative habitats was surveyed to describe establishment of the plant population. These habitats are the confines of the persistently vegetated Middle Marsh Embayment, the shoal adjacent to the embayment, and the high-current Shackleford Shoal. In February 1982, a large rectangular grid 80 m by 170 m was established in each of the three representative habitats. Each rectangle was subdivided into smaller 10- by 10-m grids. Each point of intersection of the smaller grids was assigned a number. In the field, the actual points to be sampled (20 in each habitat) were located using a pair of surveyor's transits assigned to each base station at each end of the long axis per rectangle. For each randomly selected point, the pair of angles were calculated and the intersection point marked with a stake. A 0.25-m^2 quadrat was placed on the bottom and the number of seedlings within was counted.

19. To supplement our understanding of recruitment as well as to compare natural rates of population growth versus transplanting, we measured the sexual and asexual reproductive efforts of natural and transplanted populations. This included keeping quantitative and qualitative records of the number of sexually reproductive shoots during flowering periods. We also recorded the number of viable seeds produced for individual flowering shoots and estimated this for the populations as a whole.

20. The rate of population growth and area covered were assessed in a consistent manner for all sites. At time 0 (planting day), planting units were arbitrarily selected from the units being placed in the field. These units were counted for numbers of shoots, and where appropriate, numbers of apical meristems. Planting units were also measured for bottom area covered by measuring the width of the planting on two perpendicular axes, taking the average of these two widths and using that as an average diameter (d) in meters squared in the equation:

$$\pi \, (d/2)^2 = \text{area } (m^2) \qquad (2)$$

The number of planting units surviving were periodically recorded until establishment was apparent (approximately 90 days) (Table 6). At each successive survey, ten randomly selected planting units were counted for number of shoots and area covered at each treatment using the techniques described above.

21. As pointed out by den Hartog (1971), Kenworthy et al. (1982), Fonseca et al. (1983), and Thayer et al. (1984), some seagrass meadows never form continuous meadows and remain as discrete patches due to the hydrodynamic conditions of the area. The point is that a mature meadow form in these areas is difficult to distinguish from colonizing configurations. Some of our sites displayed these kinds of meadow growth, and the area coverage models were run over more days than actually necessary to represent an established meadow, a factor that acted to depress the slope of the area coverage line.

22. Another factor that acted to depress the area coverage slopes was the inclusion of growth data from suboptimal planting sites in the model. Even though a site must have survived past the second monitoring period to be counted, the conditions at the site were such that, in an actual

mitigation project, the site may have been deemed unsuitable for planting because of its marginal environmental profile. We feel justified in including these data because they add realism to the range of growth responses that can be observed when working with these species. Therefore, our ratio of "good sites" to "marginal sites" is also an implicit factor in the final regression line. From a qualitative standpoint, the ratio was, in our opinion, never less than equal and the ratio was prevented from being negatively biased by our "growth past the second survey time" criterion.

23. The conservative growth models may call for excessive planting efforts to some sites that are recognized as being highly suitable for transplanting. Examples of these sites may be dredged sites, specifically engineered to suit seagrass growth or sites that have been damaged from short-term impacts and that need assistance in rapidly revegetating. As a consequence, we have also plotted the best-case treatment in our presentation of results on area coverage.

24. Utilization of these "best-case" lines should be done with great caution. For example, where a site meets all environmental criteria for planting and appears suitable for planting given there are adjacent meadows, one might choose to use the "best-case" line. This means fewer planting units are needed and overall costs are reduced because one expects optimum population growth. If the transplant grows optimally, the transplanter has achieved a substantial cost savings. But if for some reason the transplant does not perform as expected, the transplanter will have far fewer planting units in the field than necessary to achieve coverage in a prescribed period of time. Since there is no way to guarantee seagrass transplants any more than other cultivated vegetation, the consultation of experienced personnel is recommended in making these decisions.

25. We will discuss shoot generation rate in order to directly compare growth responses between species and different sites. Area coverage rates are a product of not only shoot generation rate, but the interaction of environmental conditions in an area which control density of the shoots. Due to this interaction, direct comparisons of area coverage models are less useful in examining actual population responses than shoot numbers by

themselves. Area coverage data are presented to show the basis for generating the planting tables used in upcoming sections. All graphs of ln shoots and area (m^2) over time are on a planting unit (PU) basis; i.e. ln shoots = ln of the number of shoots PU^{+} at time t, and area (m^2) = area in meters squared PU^{-1} at time t.

PART III. POPULATION STRUCTURE AND APPLICATION

26. The distribution and abundance of aquatic plants are the direct result of the plants' growth rates, as well as their vegetative and sexual reproductive strategies. The interactions of these factors are discussed in detail by Thayer et al. (1984). The objectives in this phase of the study were to obtain a fundamental understanding of the dynamic aspects of the population growth of the target species following transplantation. Growth parameters were selected based on information that a) describes the establishment and growth of the target species in certain habitats, as well as annual variations in these estimates and b) determines the initial quantities of plant stock required as well as the spatial arrangement for planting.

Flowering and Seedling Recruitment

27. Flowering was observed in both natural and transplanted eelgrass populations but not in shoalgrass populations. There has been no measurable sexual reproduction or seedling recruitment by shoalgrass to date. Transplanted eelgrass populations flowered in synchrony with natural populations, but the average relative abundance of flowering shoots was lower for transplanted populations (Table 7). Based on estimates of seed production for individual flowering shoots in this area (Fonseca et al. 1979; Personal Communication, 1979; R.C. Phillips, Seattle Pacific University) and the range of growth rates observed, it is estimated that a planting unit will yield between 40 and 92 viable seeds in the reproductive season following transplanting. However, data indicate that only 0.4 percent of viable seeds produced result in established seedlings. At the measured growth rates of the transplants, a yield of one viable seedling in this habitat would require between three and seven planting units.

28. Seedling recruitment by eelgrass appears to vary as a function of the specific characteristics of a site, as shown in the tabulation below.

Location	Date sampled	Seedlings m^{-2}
Middle Marsh Embayment	2/79	3.4
Middle Marsh Embayment	2/82	5.0
Shoal adjacent to Middle Marsh Embayment	2/82	1.2
Shackleford Shoal	2/82	0.0

Recruitment by seedlings was greatest in the relatively quiescent, depositional environment of the Middle Marsh Embayment, intermediate on the adjacent shoal, and absent from the high-current Shackleford Shoal. Even though flowering and seed production occur on the shoal, the establishment of viable populations from seed is a rare event. In the embayment and adjacent areas, which are depositional environments, more seeds are retained and buried. Consequently, seedlings are established in these habitats.

Shoot Generation Rate

29. The combined data of all experimental transplants are given in Figures 3 and 4 for *Z. marina* and *H. wrightii*, respectively. The specific treatments that comprise the combined data model are summarized in Table 8. A review of Table 8 shows considerable variation in the slopes of the population growth lines between years and between sites in a given year. The slopes were generally higher for the years 1978-79 for *Z. marina* and tend to increase the combined *Z. marina* population growth slope above that of *H. wrightii*. Overall, these differences are minimal and population growth rates of *Z. marina* and *H. wrightii* are virtually the same in this area.

30. Plantings were done in the fall for *Z. marina* in Beaufort as opposed to recommended spring plantings elsewhere in its distribution. *H. wrightii* was planted in late spring. Planting units at time 0 had an average of 12.7 and 15.7 shoots for *Z. marina* and *H. wrightii*, respectively. *H. wrightii* PUs had an average of 2.7 terminals out of the 15.7 PU^{-1}. A spring planting was done of *Z. marina* in Beaufort, but plantings did no more than double their shoot numbers (~ 15 to ~ 30 per PU) from May to September, during the summer stress period. These plantings exhibited normal population growth beginning in late September-October.

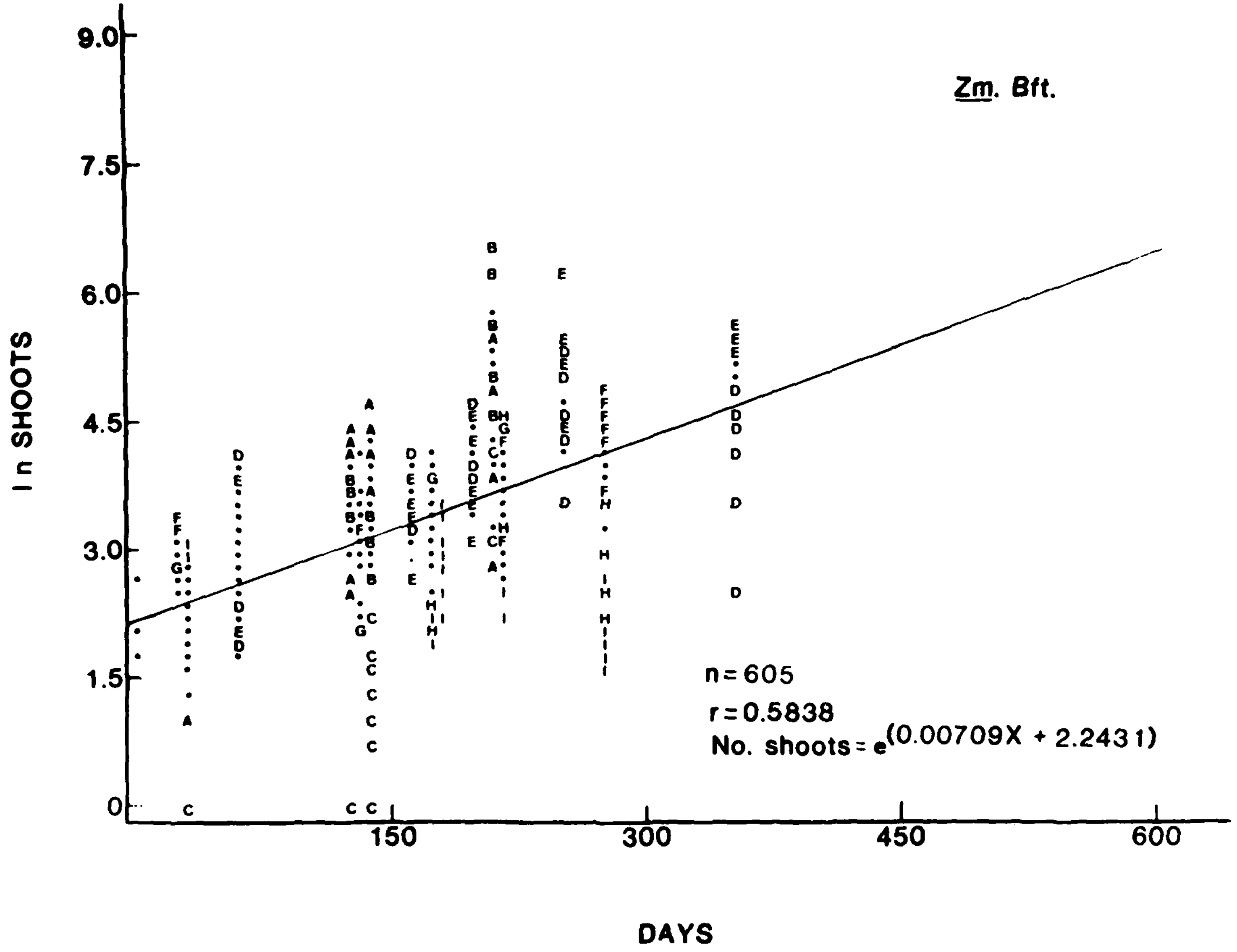

Figure 3. Regression of ln shoots/PU over time for Z. marina. Letters refer to individual planting units in different locations (Table 1).

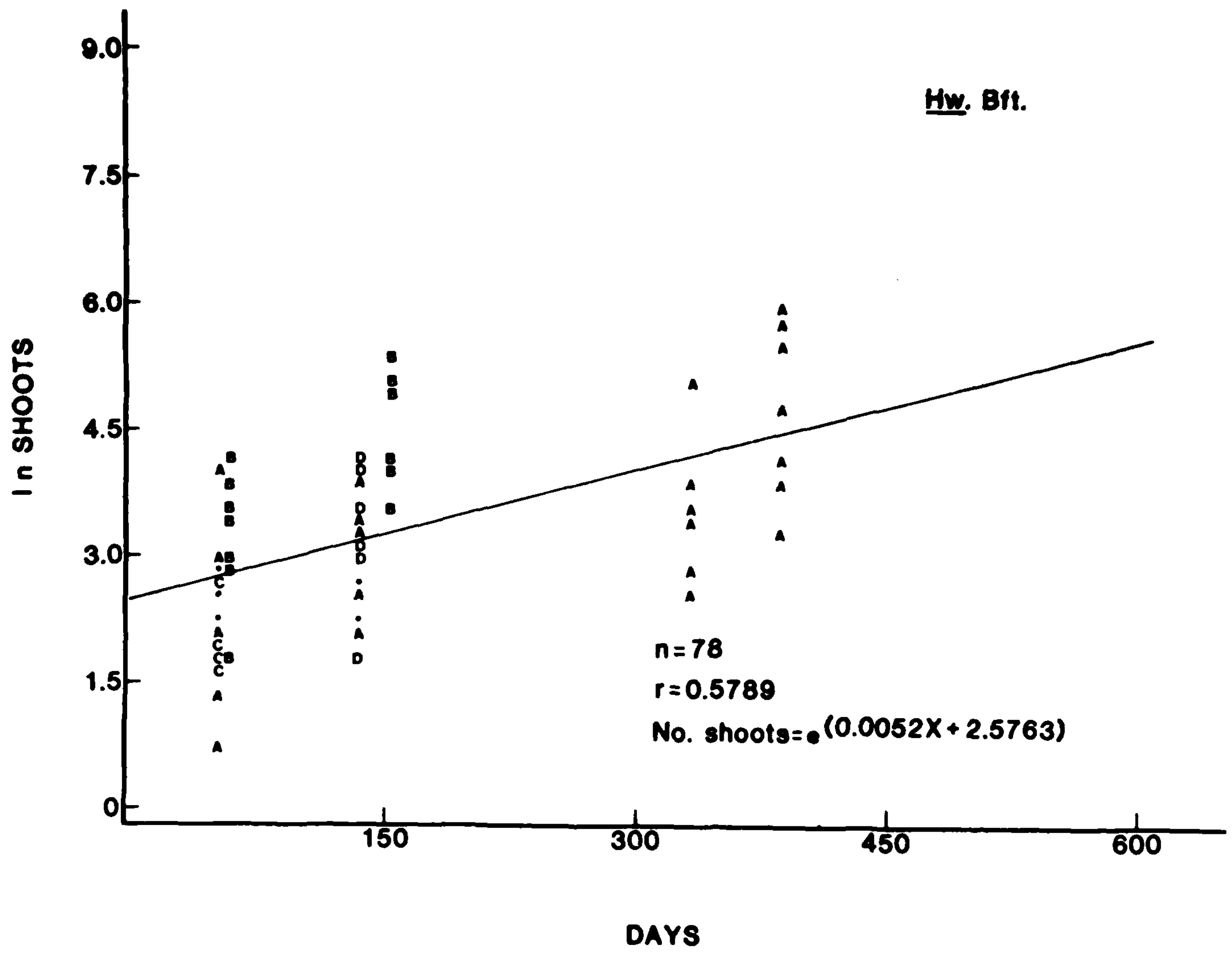

Figure 4. Regression of ln shoots/PU over time for *H. wrightii*. Letters refer to individual planting units in different locations (Table 1).

31. Stock source and the high or low energy of recipient sites did not make a consistent, significant difference in population growth rates. This contradicts earlier papers of ours that suggested the high-energy sites provided consistently faster growing stock. Transplanting stock should be collected from high-energy areas for collection efficiency.

32. All transplants near the lower depth limits of the local species distribution all did poorly. These treatments tended to make the population growth rates for each species conservative. Also, all *H. wrightii* transplants into the high-organic, low-energy site at Middle Marsh embayment died almost immediately (location: Figure 1). Their demise may be due in part to slightly higher turbidity and about 20 cm less depth there than on the adjacent shoals where plantings survived.

Area Coverage Rate

33. The regression of area (m^2) per PU for all data is given in Figures 5 and 6 for *Z. marina* and *H. wrightii*, respectively. Both figures show the overall regression and a second regression for selected, best-case situations. The application of one line as opposed to the other was discussed previously (para. 24). These two lines are utilized in planting arrangement calculations discussed in later sections.

34. One important feature of the mode of area coverage is that the final meadow form is a function of the hydrodynamic environment (Fonseca et al. 1985). This was evidenced at both *Z. marina* and *H. wrightii* planting sites in high-energy areas (Figure 1, location B) that have persisted for several years. Even though the plantings were done on 1-m centers, complete coalescence did not occur. Irregular, patchy meadows resulted, the characteristic form for this hydrodynamic regime. Having this model of meadow form prior to transplanting at a given site helps to set realistic performance standards, i.e., one would not expect and could not be held to developing a continuous coverage meadow in such environments. Transplanters must also account for this in estimating the area to be planted to meet a mitigation ratio, such as 2:1 (2 m^2 of vegetation replaced for every 1 m^2 destroyed) by planting larger areas.

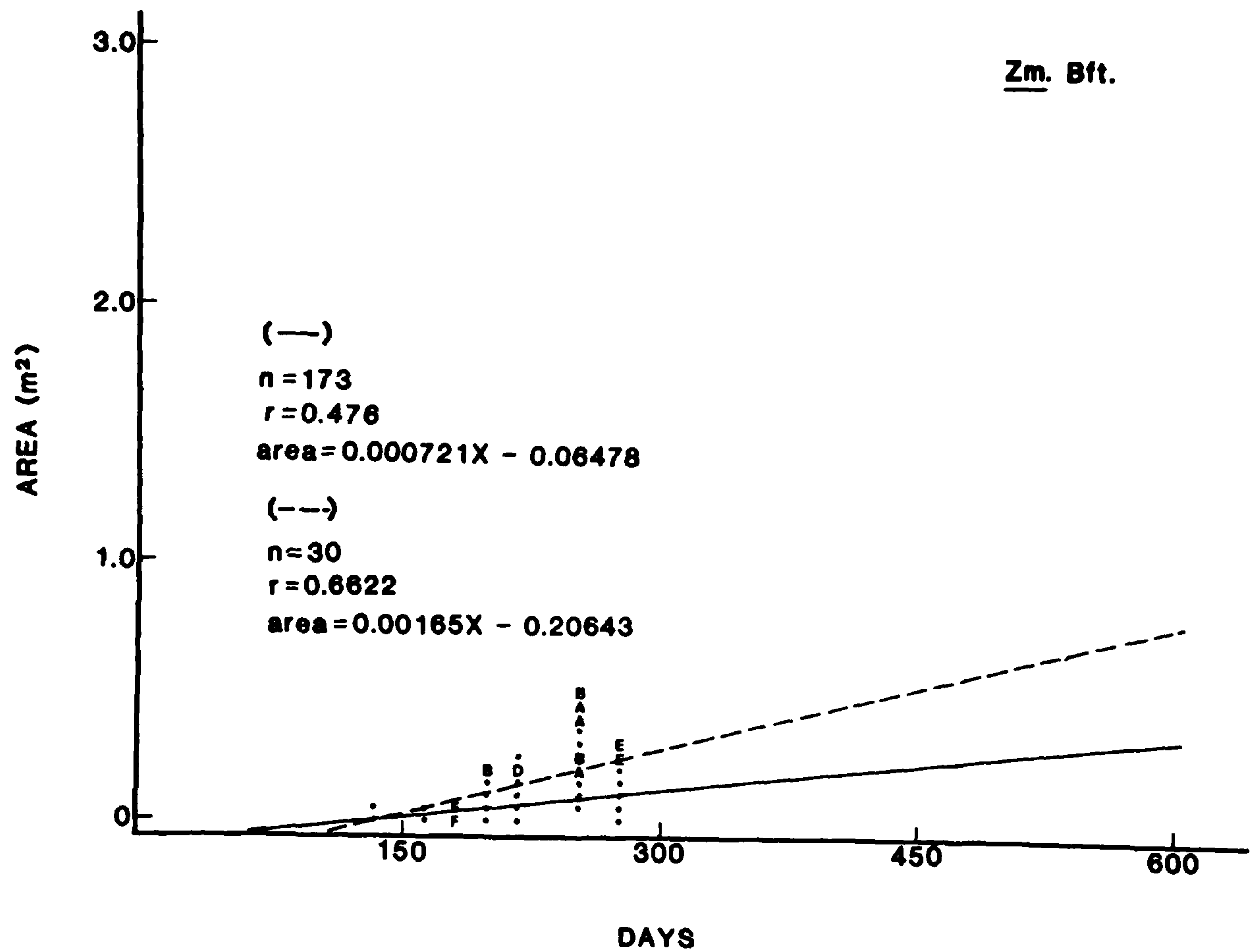

Figure 5. Regression of area of PUs over time for *Z. marina*. Letters refer to individual PUs in different locations. Solid line = all data; dashed line = best-case planting response.

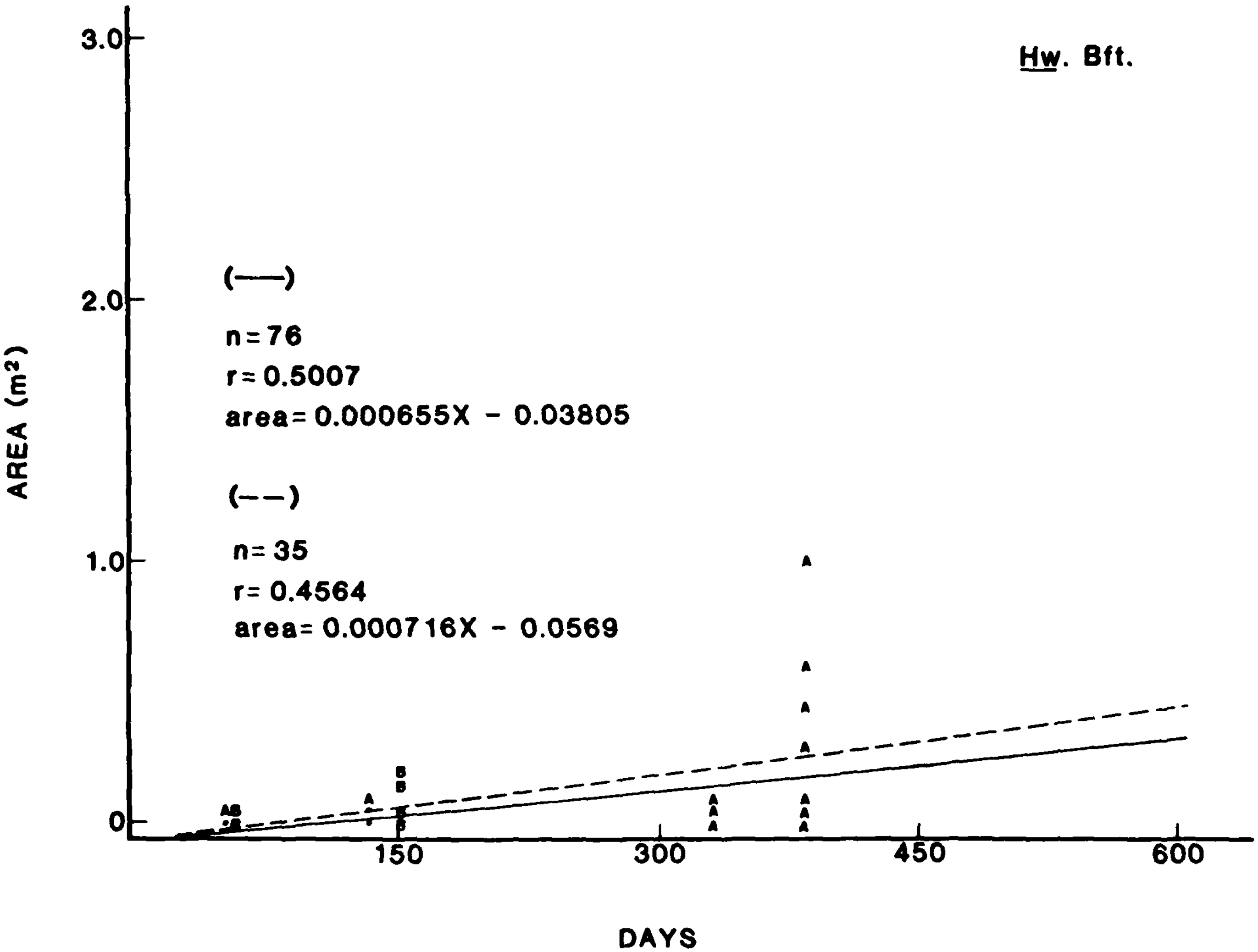

Figure 6. Regression of area of PUs over time for *H. wrightii*. Letters refer to individual PUs in different locations. Solid line = all data; dashed line = best-case planting response.

Natural Recruitment Versus Transplanting

35. In the Beaufort area the problem of seagrass recruitment is of special concern. During the past 6 years of research, no seedlings of shoalgrass were observed and only once was any evidence of attempted sexual reproduction found. Eelgrass does flower and produce seeds in this area, but recruitment by seedlings is low. Coverage of a nonvegetated site by vegetative encroachment from adjacent meadows may require long periods of time (possibly years) depending on the size of the site and proximity of viable seagrass meadows. As a consequence of these and other findings, the transplanting of mature, vegetative shoots of both seagrass species is considered a more viable technique than expecting the plants to establish populations by natural means.

PART IV. SITE EVALUATION AND DESIGN CRITERIA

36. In this section the environmental criteria used to evaluate the suitability of a site to sustain eelgrass and shoalgrass transplants are discussed. Use of these criteria will aid in the design of sediment stabilization projects to sustain seagrass transplants and hopefully create productive fishery habitat.

37. Unvegetated areas that have a history of supporting seagrass cover fall into a separate category from those that have not supported seagrass. Those that have had cover removed by a catastrophic event should continue to support seagrass growth and are prime candidates for rapid recovery through transplanting. Recovery of a site, especially a geographically isolated site, can be accelerated several years by transplanting (Kenworthy et al. 1980).

Temperature and Salinity

38. An understanding of the specific relationship between seagrasses and temperature can be used to select transplanting seasons. Phenological studies of temperate and tropical seagrasses show that their growth and development is a cyclical and seasonally recurring process. Sexual reproduction (Phillips 1980), population growth (Short 1975; Sand-Jensen 1975), and plant productivity (Zieman 1975; Penhale 1977; Jacobs 1979; Zieman and Wetzel 1980) follow recognizable patterns related to the annual temperature cycle. These seasonal patterns vary according to the location within the geographic range of the species.

39. In more northern localities, such as New England, eelgrass growth rate is highest in the spring and summer and declines in the winter; the opposite growth pattern occurs in North Carolina. Shoalgrass has peak growth during summer months in North Carolina. The optimum planting time for eelgrass in New England is in spring (Churchill, Cok, and Riner 1978). Phillips (1980) suggested that spring was optimal for areas north of Beaufort, North Carolina, through the New England coast. Orth and Moore (1982), however, demonstrated significantly greater survivorship and growth of eelgrass transplants initiated in the fall (September-October) in

Chesapeake Bay. We suspect there is a transitional area on the east coast of the United States where, depending on the severity of summer and winter temperature stresses in a given year, either a spring or fall planting would be most successful. From the work of Orth and Moore (1982), it appears that any such zone would be above the Chesapeake Bay area. We suggest that planting north of Chesapeake Bay be done in the Spring. Fall (October) is the best planting time for eelgrass in the Carolinas. Planting of shoalgrass in the Carolinas should be done in early June. Phillips (1980) recommends planting shoalgrass anytime during the year for the Gulf of Mexico and Florida although our observations and ongoing experiments indicate more rapid growth following a spring planting.

40. Plantings of each species also were done out of the recommended growing seasons. These data were incomplete but indicated a broad year-to-year and site-to-site variation in transplanting success. The probability of losing a transplant site is greatly increased by attempting to plant a species earlier in the season than recommended. Transplanting should be done at a time which maximizes the period of growth before local seasonal growth cessation. Transplanting of eelgrass near or during the time of flowering also should be done with caution. Flowering shoots senesce after seeds are released and provide no additional vegetative growth. In areas where spring plantings must be done, we suggest that the number of shoots per planting unit be increased 25 percent to account for the expression of nonvegetative flowering eelgrass. Flowering shoots will not directly contribute to bottom coverage.

41. Salinity is an especially important factor in locations where eelgrass is dominant. Although this species is fairly euryhaline, its optimum growth conditions are discrete. Vegetative growth occurs at salinities exceeding 10 ppt up to a full-strength seawater (Thayer, Wolfe, and Williams 1975; Phillips 1980). A preliminary site evaluation should take into account local species distribution and a concurrent analysis of salinity. Optimally, eelgrass should be planted in salinities above 20 ppt. Shoalgrass is more euryhaline than eelgrass, and Phillips (1980) has suggested planting ranges of 20 to 40 ppt.

Light-Depth Interaction

42. The most difficult factors to assess in seagrass transplanting are light quantity and quality. Light quantity controls photosynthetic response of seagrasses more than light quality (Dennison 1979; Wiginton and McMillan 1979; Clough and Attiwill 1980). Seagrasses have upper and lower light quantity tolerances. Their lower limit is controlled primarily by the turbidity of the water and the depth over which that turbidity may act to attenuate down-welling radiation. The upper limit of seagrass tolerance is controlled by light saturation and, more importantly, exposure and desiccation during tidal cycles.

43. The upper limit of transplanting is more easily identified when surveying a potential site or designing a new one. The upper limit for a transplant should be a point where the seagrass is always covered with water. This usually is at or below mean low, low water (MLLW). MLLW can be determined by consulting tide charts and measuring the depth to which the tide retreats on the lowest point in a lunar cycle during the local seasonal stress (usually temperature and/or desiccation). Another method of upper limit assessment is to record the depth to which local seagrasses occur relative to MLLW. This is especially true in areas of the Northwest where eelgrass grows intertidally. Intertidal plantings for most areas are not recommended, however. Net photosynthesis is reduced at least one-third during exposure (Clough and Attiwill 1980) and may provide additional (and possibly terminal) stress during transplanting.

44. Determining the lower depth limit of a transplant that will sustain seagrass growth is more difficult. Estimates by different techniques have described light saturation and limitation for seagrasses. McRoy (1974) describes carbon uptake by eelgrass as being 0 at approximately 1.2 percent of insolation (all incoming solar radiation), half saturation at 12.5 percent, and full saturation at 50 percent of insolation. Backman and Barlotti (1976) demonstrated a significant reduction in shoot number in an existing eelgrass meadow by reducing down-welling radiation to 37 percent of the ambient value. Penhale (1976) concluded that light saturation levels of eelgrass in North Carolina were higher than in boreal areas due to adaptation to a different solar regime. Wiginton and McMillan (1979) and Clough and Attiwill (1980)

agree that photon flux density (PAR) limits the depth of seagrass distribution. Wiginton and McMillan (1979) note that because of differences in turbidity, photon flux density at -1 m in Texas can be similar to that at -12 m and -19 m in St. Croix, U. S. Virgin Islands. Clough and Attiwill (1980) had 35 percent incidental PAR in Z. muelleri meadows in Australia. Congdon and McComb (1979) determined that Ruppia maritima was most productive at -10 m MSL and above -0.50 m MSL; exposure at low tide limited its distribution.

45. Stuart (1979) surveyed eelgrass distribution in the Beaufort, North Carolina, area and found that biomass approached 0 at -0.40 m below mean low water. Survey data from this study indicate that negative shoot production, or shoot loss, occurred at 1.17 percent PAR, a value close to that of McRoy (1974) (Tables 2 and 8). However, at a 1.43 percent, PAR, r was considerably higher. This suggests that while the lower light limit of eelgrasses is discrete, the variation between sites and/or season may be quite large. This indicates that although the estimated average annual value of light may sustain growth one year, the same site can become unsuitable another year because of the timing of increased turbidity, especially during the growing season. It is recommended that McRoy's 12.5 percent PAR value for half saturation be used to describe the reliable depth limit of seagrass transplants. In the Beaufort area, the depth associated with optimum light quantity may be quite shallow. The shallowest site (Dredged Material Island, shallow, Table 2) was also the site with the highest average light. The light level, however, was only 36 percent of PAR. It is suspected that this area suffered from occasional exposure which suppressed growth.

46. The shallower sites in the Middle Marsh Embayment plantings grew well initially. However, in the early summer when they were frequently exposed during clear hot days, nearly all plantings died. The 1978 Middle Marsh Embayment plantings that were in areas 20 cm deeper than the other sites continued to grow well for at least two growing seasons. This shows the critical role depth plays in quiescent sites where exposure and subsequent high temperature may be lethal.

47. If light measuring instruments are not available, the distribution of natural seagrass meadows contiguous with the site should be used as an indication of suitable light, depth, and exposure conditions in

the planting area. Noncontiguous sites may provide inaccurate estimates of conditions at a planting site. For example, Table 2 shows two sites that are only 200 m apart (Middle Marsh Embayment and Shackleford Shoal), that have k values differing 24 percent.

Use of Dredged Material

48. The hydrodynamic characteristics of a planting site can greatly influence the success of establishing seagrass cover. High-current velocities cause variation in the direction of growth of transplanted species and affect recruitment by seedlings. When creation of a site involves use of dredged material, proper placement of the material can help to create a stable site of a depth suitable for transplanting. The creation of a semi-enclosed embayment with adequate circulation is recommended. A dredged material island with an open embayment facing away from prevailing winds during the season of lowest seagrass growth for that area would be ideal. Exposed portions could be stabilized by emergent vegetation assisted by sandbags and wave-dampening devices such as tire breakwaters or plastic grass buffers.

Sediment Characteristics

49. Kenworthy, Zieman, and Thayer (1982) found that growth of naturally established seagrasses is not limited by sediment type. Kenworthy and Fonseca (1977), however, showed that sediments that have undergone treatment similar to some dredged material placement procedures can cause reduced growth under transplanting conditions. Dredged sediment should be allowed to stabilize for at least a month (Kenworthy and Fonseca 1977) to allow a natural sediment chemical profile to develop. Polluted sediments such as those from industrial harbors should not be used as seagrass transplant sites.

Sediment Fluctuations

50. Sediment flux rate should be used as an indicator of sediment stability and the potential for burial-erosion events at a given site. For this reason, planting unit survival success after 50 days was plotted versus corresponding sediment flux rate (SFR) at a site (Figure 7). With time 0 being planting time, 50 days is the approximate time required for planting units to develop root systems and become independent of the anchoring device. Since the relation of sediment fluctuation rate to planting unit survival is actually a test of anchoring efficiency, this relationship should be similar for most seagrass species of similar foliar dimensions.

51. A sediment fluctuation rate of 0.098 cm/day (50-day average) correlates with a 50-percent loss in planting units. It is recommended that this value be accepted as the maximum allowable fluctuation rate for an unprotected transplanting site. Any values greater than this warrant careful consideration of the use of wave and current reduction devices to minimize planting unit loss.

Monitoring

52. Documenting the manner in which environmental conditions affect the suitability of a site requires flexibility and versatility in personnel. The variability one encounters in collecting field data precludes any firm rules about site evaluation criteria. It is for this reason that the criteria presented in this report are given as recommended guidelines. The best available information one can develop for a potential site is a reflection of the precision, accuracy, and frequency of its collection. Many of the site evaluation criteria are time-dependent variables. For example, light quantity changes between days, seasons, and years for a given site, especially since variation in turbidity is a function of meteorologic conditions, a stochastic process. For these reasons, data collection of certain environmental factors could proceed virtually indefinitely without any predictable patterns emerging. Based on the data presented in this report and observations on transplanting from 1978 to the present, monitoring procedures for the site evaluation criteria have been summarized (Table 8).

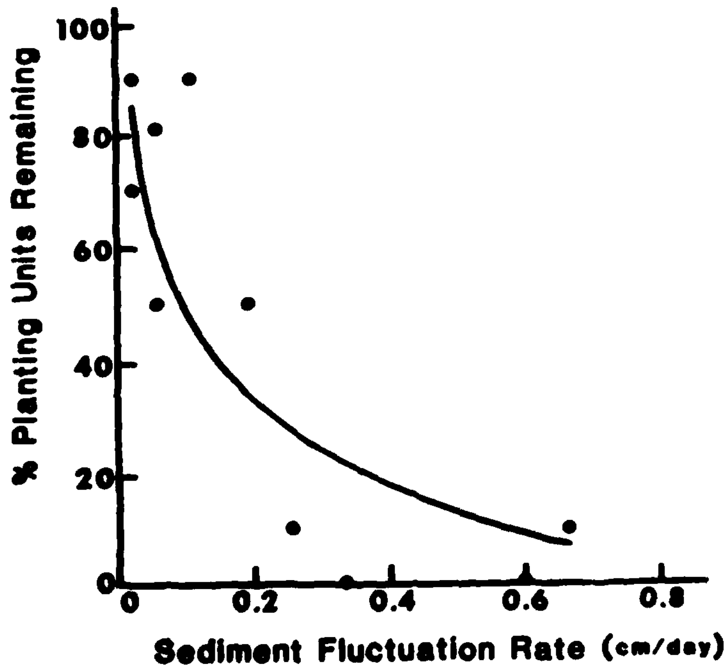

Figure 7. Sediment flux rate and plant mortality. The relation between the absolute value of sediment fluctuation (+/-) on a 50-day average for transplanted eelgrass and shoalgrass sites and the resultant loss of plant units (expressed as percent remaining). The equation for the line is: $Y = a + b \cdot \ln(x)$, where: $a = -4.666$, $b = -23.225$, and $r^2 = 0.84$.

Pilot Plantings

53. A small-scale pilot planting is a useful technique for assessing the suitability of a potential planting site. Measuring the growth and observing the establishment of transplants yields direct evidence as to whether the site can or cannot support seagrass growth. Pilot plantings should be placed sparsely but evenly across as many gradients of environmental factors (Table 9) as possible. By this method, portions of the site in which transplants may require protection can be identified (e.g. tire breakwater for wave dampening).

54. The major drawback to this method is that pilot plantings must be initiated during the appropriate planting season. To assess accurately the response of the plants to that site, monitoring of the transplants must proceed several months. If the seagrasses in the pilot have a positive growth response, the next earliest planting time would be the following year. One must then consider the year-to-year variation in growth ($\pm$ 50 percent) and determine the effects this might have in planting the site.

PART V. TRANSPLANTING PROCEDURE

Success

55. "Success" has been used to describe many seagrass transplants, both in a positive and negative sense. A transplant is considered successful if planting units yield a shoot generation or bottom coverage rate comparable to either natural, local seagrass populations (preferable) or to literature values for successful transplants. Any deviation in shoot generation rate from either of the two reference data sets described above can be tested statistically. Another measure of success is to determine if the transplant retained a major portion of the planting units. For example, Table 6 shows the survival rates of planting units during this study. Although the eelgrass planting at the shallow Dredged Material Island site lost 44 percent of the planting units, the survivors have displayed a growth rate comparable to other sites (Table 7).

56. The length of time a transplant remains does not necessarily determine the efficacy of the technique, success of transplanting at that site, or of transplanting in general. Since we have no way of accurately predicting catastrophic events (storms, ice shearing, etc.), any chosen time period used to measure success must be considered arbitrary.

57. It is important to sustain a seagrass planting if sediment stabilization and biological habitat development are to be achieved. Mitigation plans may have a time requirement for unassisted endurance of a transplant (usually 2 years). This ensures that a contractor will deliver a product, but also allows for the release of that contractor from replanting a chronically perturbed site every few years in perpetuity even though it may fall within the recommended planting guidelines. A time limit of a transplant should not be confused with success of a transplant. Realizing this, we should not allow destruction of a seagrass meadow that will be difficult to restore.

Planting Table Calculation

58. A table was developed to facilitate computation of planting site arrangement. This table was derived from the growth of our experimental transplants. Growth of transplants should be determined through monitoring of the rate of whole shoot addition to the population, rate of area covered per planting unit, and number of planting units remaining. Shoot generation and coverage rate data have been collected for eelgrass and shoalgrass transplants under different current regimes (high-energy shoal and low-energy embayment). Current regime is defined by velocity as described by Fonseca et al. (1983). Each current regime has characteristic sediment types and other environmental conditions that influence seagrass shoot generation and coverage rates for these species between sites and within a site in different years. From these data, planting techniques have been developed which provide predictable coverage rates.

59. The rates of increase in planting unit areas are given in Table 8 and were calculated from the equation:

$$Y = mx + b \tag{3}$$

where: Y = area covered per PU in m^2

X = number of days

M = slope for regression of area covered on time (days)

b = y-intercept of regression line.

Area covered by planting units Y was calculated in increments of days (Table 10). To calculate cost, number of planting units needed, grid spacing, and time to complete cover, the user selects a Y value based on desired species and time to complete cover (250 days is recommended for eelgrass and 150 days for shoalgrass, each of which equals about one growing season on the mid-Atlantic coast). One then divides the area to be planted (m^2) by the Y value to obtain the number of planting units needed to gain a complete meadow in the chosen number of days (Fonseca et al. (1979) demonstrated that for eelgrass, 15 shoots/planting unit is most efficient).

60. Operation costs are estimated as follows:

Decision

↓

Species and number of days to coverage

Calculate number of planting units needed

↓

Decision

SCUBA assisted ⇦ ⇨ non-SCUBA assisted

SCUBA assisted	non-SCUBA assisted
regular hourly wage X 0.0119*(man-hour/planting unit)	regular hourly wage X 0.0205(man-hour/planting unit)
+	
SCUBA hourly wage X 0.0054(man-hour/planting unit)	

↓

Intermediate cost per planting unit depending upon SCUBA use.

* If all workers are not of equal pay, take mean hourly wage of all non-SCUBA workers. *Values are determined by field trials.*

Intermediate cost/planting unit is multiplied by a factor of 1.2 to include material costs in fabrication; this equals total cost/planting unit. The total cost/planting unit is then multiplied by the total number of planting units needed for planting to obtain total operation cost. One either accepts or rejects this cost. If cost is rejected, return to the table and select a longer time for a lower cost. If accepted, then calculate the grid spacing as follows: $\sqrt{\text{area (m}^2\text{)/number of planting units}}$ = approximate spacing between plants in a grid pattern (m) to attain the selected coverage in the time given.

61. Current velocity and direction affect the pattern of coverage substantially. When current velocity regularly exceeds 50 cm/sec daily, grid spacing should be expanded at least 10 percent perpendicular to the major axis of reversing current flow and reduced 10 percent on the major axis of current flow direction. Under reversing tidal current flow, the

planted shoots tend to propagate in the direction of least resistance, which is normal to the major axis of flow. Exposed areas, especially those exposed to wind-driven waves, should be planted at higher densities (as much as 50 percent higher) to facilitate a more complete stabilization in a minimum of time. A planting unit takes approximately 50 days to begin development of its root-rhizome attachment. These 50 days are a critical time when most planting unit losses will occur; increased planting density will not necessarily prevent this loss. The above alteration of grid spacing will aid in the creation of continuous cover under the time selected in the planting table.

62. The values in Table 10 are based on the average meadow configuration of all current areas. The embayment area studied is a low-relief, low-current area, high in sediment organic content and silt and clay fractions, and eelgrass grows in broad, continuous meadows. On shoal areas, however, growth results in discrete patches with a higher relief referred to as mounds. The eelgrass plantings on the high-current shoal coalesced to some extent on the axis perpendicular to the current after 600 days, but have not formed a continuous meadow. They maintain themselves as visibly discrete patches. One should not expect to attain complete cover on a transplant site if the natural populations do not attain that configuration under similar current and sediment conditions.

Estimating Plant Material Requirements

63. To calculate the number of planting units needed for a transplant site, solve Equation 4:

$$\text{Number of PUs} = \frac{\text{area of transplant in square meters}}{Y} \qquad (4)$$

To calculate the spacing between planting units, solve Equation 5:

$$\text{Distance between PUs in meters} = \sqrt{\frac{\text{area of transplant in square meters}}{\text{number of PUs}}} \qquad (5)$$

where Y value is selected from Table 10.

64. The number of shoots harvested is calculated as follows:

$$\text{Number of planting units} \times \frac{\text{number of shoots}}{\text{planting unit}} \qquad (6)$$

where number of shoots/planting units = 15 mature, vegetative shoots (applicable to both eelgrass and shoalgrass; this should provide enough apical meristems in the case of shoalgrass).

Estimating Labor

65. Estimates of labor costs for harvesting, preparation of planting units, and planting are based on the following guidelines developed from our labortory and field surveys.

a. Harvest rate is about 18,000 shoots per man-hour, based on timed trials.
b. Fabrication rate of planting units is approximately 100/man-hour based on timed trials.
c. Planting rate is about 150 planting units/man-hour for most habitats.
d. SCUBA assisted workers can plant at least 15 percent faster than wading, non-SCUBA assisted workers, but wage differences make using non-SCUBA workers the more economical procedure.

66. Given 1 acre of eelgrass planting and complete cover desired in 250 days, the man-hour cost per hectare is estimated as follows:

Activity	Man-hours
Harvest	29
Preparation	351
Planting	234
Total	614

These estimates are based on the mean instantaneous coefficients of growth (area covered) for each species over all sites. The data in Table 8 show a wide variation in growth rates by site, with a dominance of slower growth values. Therefore, the above labor costs are higher than those previously reported, although the predicted coverage rates are conservative.

Harvest and Storage of Plant Materials

Identifying preferred harvest sites

67. Eelgrass harvested from high-current areas may yield superior transplanted growth rates relative to plants harvested from low-current areas (Fonseca et al. 1979), although the rates may vary from season to season. High-current areas provide transplanting stock with good rhizome mat integrity and collection efficiency. High-current areas, defined as those whose surface current velocities often exceed 50 cm/sec, are characterized by discrete, raised patches of grass on a sandy, low-organic soil (usually < 2 percent organic material) (Figure 8).

68. Shoalgrass also should be collected from high-current areas for reasons similar to those given for eelgrass. Each leafy shoot of shoalgrass, however, does not reproduce vegetatively as does eelgrass. Vegetative reproduction occurs at a higher frequency with terminal or adventitious shoots (Tomlinson 1974). The percentage of terminal shoots was determined for various sites in donor beds and edge-center positions within those beds. Such a percentage is used as a relative indicator of active vegetative growth for the purpose of stock selection for transplanting.

69. An average of five 15.3-cm-diam cores were taken at each sampling site to determine the percentage of terminal shoots. The accompanying sediment in each core was washed free and both a terminal and total shoot count were performed. These counts were summed over all cores from a given site. All surveys were completed during the summer months to monitor plant conditions during the recommended season for transplanting. The data indicate that large differences occur between and within sites for the percentage of terminal shoots harvested (Table 11). It is recommended that similar field surveys of local available transplanting stock be performed before carrying out a shoalgrass transplant.

Harvest technique

70. Sods of seagrasses are dug with a shovel to a depth of at least 20 cm to include the whole root-rhizome complex and rinsed free of attached sediment at the site. If care is taken to maintain the carpet-like integrity of the rhizomes, planting unit preparation will be easier.

Figure 8. A typical mound of high-current area eelgrass. Note the isolated and elevated nature of the seagrass. The same formation is found for shoalgrass except that the mound may be many times farther across (scale of this mound is 1 m).

Storage guidelines

71. Sediment-free mats of seagrass should be stored in ambient seawater and processed into planting units within 36 hr. Aeration of the storage containers (plastic trashcans work well) is often required to prevent anaerobic conditions. Setting the mats in shallow flowing seawater tables works well and affords an ideal working area for preparation of planting units.

Preparation of Planting Units

72. Preparation of a planting unit is a four-step procedure: (a) seagrass is dug up and rinsed free of sediment at the site, taking care to maintain the integrity of the root-rhizome complex; (b) shoots are pulled in clumps from the dug-up mats to make planting units (15 shoots per planting unit are recommended), taking care to hold the clump of shoots upright; (c) a third of a metal coathanger (precut and bent to an L or U shape) about 20 cm long is added to the clump of shoots, wound with a piece of bonded construction paper (file cards cut in strips work well), and secured with twist-ties to form the finished planting unit (Figure 9). These may be carried to a planting site covered with water in small manageable containers.

73. Shoalgrass shoots occur at intervals along the rhizome. Approximately 15 shoots with as many terminal shoots as possible should be included in each planting unit. In some areas, shoalgrass meadows have long rhizomes whose distal portions containing a terminal meristem are unattached to the sediment and wave freely in the water column, a stoloniferous-like growth form. These long "aerial" runners (rhizomes) make excellent transplanting stock and are easily collected (Personal Communication, R.R. Lewis and J. Derrenbacker, August 1981, Mangrove Systems Inc.). Since it is difficult to orient the rhizomes vertically on the anchor, it is recommended that they be attached to the top L- or U-shaped portion of the anchor so that the rhizome is perpendicular to the long shank of the anchor (90 deg to the attachment shown in Figure 9) and will lie flat on the sediment surface when the unit is planted. Approximately, three rhizomes harvested with at least 5 shoots per rhizome should constitute a planting unit.

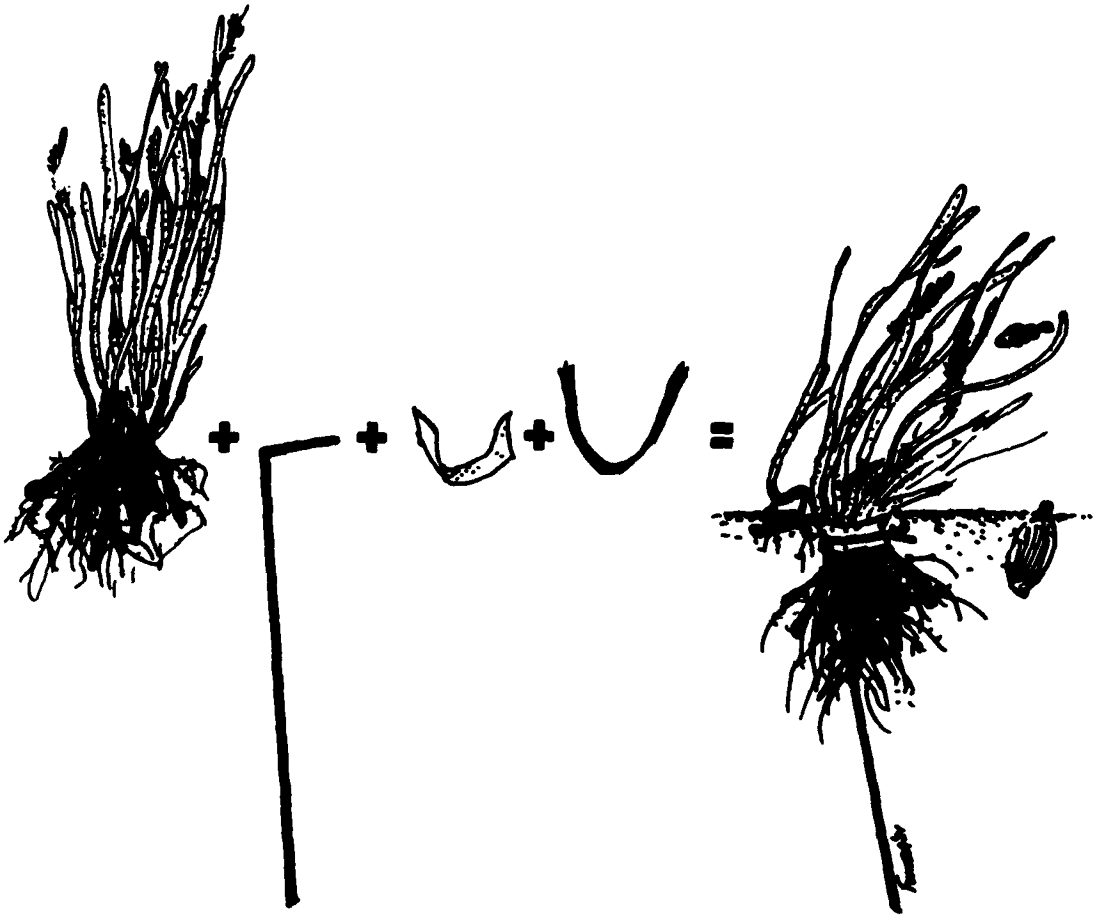

Figure 9. Breakdown of the components of a planting unit for use in all habitats. From left to right: a group of approximately 15 shoots, metal anchor (20 cm), paper collar, and wire tie.

Planting

74. Proper planting of the seagrass is a critical factor in its survival. Insertion of the plants to the same or a slightly greater depth than they grow naturally, taking care to cover the top of the anchor, is a stringent requirement (Figure 9). Since seagrasses tend to propagate vegetatively in the direction of least resistance, the down-current spacing in high-current areas should be shortened 10 percent and the cross-current spacing lengthened 10 percent.

75. Planting units are easily inserted, even in compacted sand, by the creation of a lead hole (a heavy dive knife works well). Shoalgrass plantings with horizontal attachment will rarely need such a lead hole.

76. Logistic problems encountered in high-current areas result from diver instability and lack of orientation. The use of extra weights and premarked intervals on leaded lines laid down-current circumvents most problems. Work must be done facing into the current. Use of boards or snowshoes to traverse very soft-bottom sites is suggested. Using snorkels or SCUBA at a higher tide will prevent the fatigue and planting site disturbance created by walking around the site without walking boards or snowshoes.

PART VI. SEDIMENT MODIFICATION AND STABILIZATION

77. The influence of seagrass transplants on sedimentary processes is poorly documented. Churchill, Cok, and Riner (1978) and Kenworthy et al. (1980) report shifts in surface sediment composition to more silt and clay fractions in quiescent vegetated areas. Ranwell et al. (1974) reported small transplanted plugs trapped sediment up to 2 cm above the surrounding mudflat. Ranwell also noted that the plug transplants survived 3-cm variations in sediment height in 8 days. This is similar to fluctuation rates observed during this study at transplanting sites.

78. The influence of transplants on sedimentary development was investigated through three short-term surveys. The three surveys were (a) the effects of canopy denudation on entrapped sediment, (b) surface sediment particle-size surveys inside and outside existing transplanted patches, and (c) volume of sediment trapped in planting units over time.

Denuding Survey

79. Two natural mounds of eelgrass with an elevation of $\approx$ 8 cm and a diameter of $\sim$ 1 m were denuded of foliage by clipping the shoots off just at or below the sediment surface. This was done to measure the degree of instability that the loss of foliage would have on the seagrass meadow bathymetry. Shear velocity decreased as much as 300 percent following denuding, indicating a transfer of momentum to the sediment surface. The mean sediment surface height dropped 0.5 cm on the mounds within 2 hr of denuding in the presence of 28 cm/sec current velocities. After that time, these mounds remained constant in elevation, while five adjacent natural mounds fluctuated 1- 2 cm in elevation during the 10-day interval. Measurements of the denuded mounds were stopped after 7 days due to loss of reference stakes. Exposure of the rhizomes shortly after denuding (1 day) coincided with a reduction in erosion since the mound height remained relatively constant. The sediment surface of the denuded mounds began to rise concomitantly with an overall short-term shoal accretion and initiation of eelgrass shoot regrowth after 7 days.

80. Preliminary observations made during ongoing hydrodynamic research indicated that shoalgrass has a substantially greater resistance to sediment erosion than eelgrass because of a better root-rhizome mat integrity. Observations of the denuded eelgrass mounds should underestimate predictions of stabilization potential when applied to shoalgrass plantings.

In/Out Surface Sediment Survey

81. Comparative surveys inside and outside the planting units were made when the transplants visually exhibited sediment accretion. SCUBA divers used small spatulas to collect samples of the top centimeter of sediment from the inside of at least five randomly selected planting units. A comparable number of "outside" samples were obtained in the same manner from the unvegetated area neighboring each randomly selected planting unit. The same procedures of sediment analysis previously discussed were used. The data are summarized in Table 12.

82. The results indicate no substantial difference in surface sediment composition in and out of the planting units (avg. diam $\simeq$ 20 cm) after $\simeq$ 250 days (Table 12). The Dredged Material Island site had more silt and clay but less organic matter overall at the time of sampling than the Shackleford Shoal site. Both sites were well-sorted fine sands. Distribution of the sands was only mildly leptokurtic, but skewed to fine and coarse sediments for the Dredged Material Island and Shackleford Shoal sites, respectively.

83. Work by Fonseca et al. (1982) has demonstrated current-velocity reduction in eelgrass meadows by a factor of 1.25 cm/cm sec^{-1} of velocity. Therefore, these small planting units of eelgrass should be easily scoured at velocities around 16 cm/sec, accounting for the negligible sediment difference inside and outside the eelgrass.

Sediment Trapping

84. Mound volume is a calculated estimate of average volume of sediment entrapped by the seagrasses extrapolated to a hectare of transplanted bottom. It is used as a comparative measure of the local effect

of the plants on sediment entrapment. Three surveys of the eelgrass transplants were completed: two surveys after a period of one growing season (≈ 250 days) and one survey after two growing seasons. The average difference in sediment surface heights inside and outside transplanted units at the sample times provided change of sediment height information as effected by the transplanted units (ΔH). When combined with population dynamics measurements, such as average area covered by the average planting unit (A), mound volume can be calculated as follows:

Assuming an ideal model of a disc-shaped sediment mound with an average increase in height ΔH and extrapolated cross-sectional area A at time t,

$$\Delta H \times A_t = \frac{\text{volume sediment retained } (m^3)}{\text{planting unit}} \text{ at time } t \qquad (7)$$

With an observed transplant survival rate of 90 percent, and 10,201 planting units/hectare (corresponding to 1-m centers)

$$\frac{\text{volume of sediment } (m^3)}{\text{planting unit}} \times \begin{array}{c}\text{survival rate of}\\ \text{planting}\\ \text{units/hectare}\end{array} = \frac{\text{volume of sediment } (m^3)}{\text{hectare of transplants}} \qquad (8)$$

85. The data are summarized in Table 13. Sediments accumulated above the surrounding bottom during periods of peak seagrass biomass similar to observations by Churchill, Cok, and Riner (1978). The values given in Table 13 indicate that seagrasses on a short-term basis (2-3 yr) do not account for substantial accretion or retention of sediments (only 1-3 cm above the natural bottom) in open-water areas. Comparative measurements in the embayment (quiescent) area were not made before a seasonal dieback of eelgrass or in the shoalgrass. The development of eelgrass meadows described by Fonseca et al. (1983) suggests that the meadows are limited in their mounding or accretion because of hydraulic and exposure limitations.

PART VII. SUMMARY AND CONCLUSIONS

86. Based on extensive observations and measurements of seagrass systems, study sites were selected that represent a wide range of environmental conditions under which eelgrass and shoalgrass locally exist. The environmental factors considered were temperature, salinity, light and depth, sediment characteristics, and hydraulic regime. Temperature and salinity ranges were stenotypic across the sites. But light and water depth and hydraulic regimes (which control sediment characteristics) were subject to wide variations and probably had intrinsic control over the distribution of the seagrasses. Annual temperature and salinity for all sites ranged from 9° to 28° C and 24 to 36 ppt, respectively. Light and depth interactions produced light energy variations from 1.2 to 36 percent of incident photosynthetically active radiation. The hydraulic regimes of the study sites were described by currents ranging between sites from 2.5 to 92.0 cm/sec and sediment height changes up to 0.6 cm/day (50-day average).

87. Three fundamental questions regarding the feasibility of establishing seagrasses on new sites could be resolved by a study of their population dynamics: (a) will establishment occur by natural recruitment, (b) are we able to predict growth rates of transplanted species with confidence and, given that this is true, (c) can seagrass habitat development be accelerated by transplantation?

88. To answer these questions, fruiting and seedling recruitment was examined for both species. Shoalgrass has not been observed to reproduce by seed in this area. Eelgrass reproduces sexually but, even in apparently optimum recruitment areas, the establishment of five eelgrass planting units (approximately 75 shoots) is required to produce one successful seedling per year. Given the local status of sexual reproduction (which is not unlike other geographic areas), and the geometric problems of vegetative encroachment if natural meadows exist adjacent to the planting site, transplanting for the establishment of new seagrass habitat is recommended. Mean vegetative growth rates can vary 25-50% from the values presented here depending on local environmental conditions. Assuming all site evaluation criteria are met, recovery of appropriate areas can be accelerated dramatically by transplanting eelgrass and shoalgrass, often by time measured in years.

89. Recommended guidelines for site evaluation by critical environmental factors are presented. These factors are temperature, salinity, light depth, hydrodynamics, sediment characteristics, and fluctuation. The recommended limits and monitoring procedures are summarized in Table 9. Site design guidelines for sediment stabilization concentrate on placing nonchemically polluted material at an appropriate depth while maintaining the physical integrity of the site. Semienclosed embayments protected from prevailing winds are suggested. Unconsolidated sediments may be protected by artificial wave-dampening devices until seagrass transplants coalesce, as well as by conjunctive planting with other plant species across adjacent intertidal habitat.

90. Successful seagrass transplants should display new shoot generation and coverage rates similar to natural or other documented transplant populations. Transplant stock for either species should consist of mature, vegetative shoots preferably collected from high-current areas. Shoalgrass stock should have a high percentage of terminal shoots. Bundles of shoots are attached to anchors and planted. Equations are given for determining amount of transplant stock and spacing required to cover sites in a specified number of days. About 600 man-hours are required per acre of bottom planted. Planting may be done by wading or SCUBA-assisted workers depending on water depth.

91. The major value of seagrasses in sedimentary dynamics is stabilization, rather than accretion of sediments. This was shown by the stabilization of the bottom sediments by roots and rhizomes after foliar removal, the similarity of sediments in and out of planting sites, and the minimum accumulation of sediment by the transplants after 2 years. Findings presented by Churchill, Cok, and Riner (1978) and Fonseca et al. (1982, 1983) also show that sedimentary accretion appears to be balanced by erosion.

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Table 1

Planting Sites

Site Name	Figure 1 Referenced Location	Date Planted month/year	Species (source)*	Spacing	Planting Units (PU)	Dimensions for Plots
Middle Marsh Embayment	A	10/78	Eelgrass (1/2 H, 1/2 L)	1m	392	8 - 6x6 m blocks with 49 PU/block
Shackleford Shoal	B	10/79	Eelgrass (1/2 H, 1/2 L)	1m	100	1 - 9x9 m grid
Shackleford Shoal	B	6/81	Shoalgrass (H)	1m	960	2 - 16x30 m grids, one deep, one shallow
Dredged Material Island (3 years old, planting time)	C	6/81	Shoalgrass (H)	1m	200	2 - 9x9 m grids, one deep, one shallow
Barden Inlet	D	6/81	Shoalgrass (H)	1m	90	2 - 45-m rows
Ocracoke Island	not shown	7/81	Shoalgrass (H)	1m	100	1 - 9x9 m grid
Bigfoot Slough	not shown	7/81	Eelgrass (H)	1m	100	1 - 9x9 m grid
Middle Marsh Embayment	A	7/81	Shoalgrass (H)	1m	100	1 - 9x9 m grid

(Continued)

Table 1 (Concluded)

Middle Marsh Embayment	A	10/81	Eelgrass (H)	1m	100	1 - 9x9 m grid
Shackleford Shoal	B	10/81	Eelgrass (H)	1m	90	3 - 30-m rows
Middle Marsh Embayment	A	6/82	Shoalgrass (H)	1m	100	1- 9x9 m grid

* Planting stock derived from high-energy (H) or low-energy (L) environment.

Table 2

Summary of Light Data and Bathmetry Information at Several Transplant Sites

Location	k*	Bathmetry Z (relative to MSL)	% PAR at Bottom**
Dredged Material Island			
shallow	4.453	-0.224 m	36.80
deep	4.453	-0.999 m	1.17
Shackleford Shoal	3.990	-1.052 m	1.43
Middle Marsh Embayment	5.259	-0.705 m	2.45

* k = average annual attenuation coefficient.

** PAR = Photosynthetically Active Radiation (calculated with the equation $I_Z = I_0 e^{-kz}$, where I_Z = radiation at depth Z, I_0 = radiation at the surface, e = base of the natural log, k = average annual attenuation coefficient).

Table 3

Surface Sediment of Transplant Sites

Date	M (mean particle size)	So (sorting)	Sk (skewness)	Ki (kurtosis)	% OM (organic matter)	% S-C (silt-clay)
			DREDGED MATERIAL ISLAND - SHALLOW			
6/25/81	2.132	0.809	-0.268	1.686	0.74	0.53
8/13/81	2.470	0.558	0.196	1.256	0.80	3.05
11/19/81	2.830	0.791	-0.260	1.001	0.93	2.10
3/11/82S*	2.235	0.550	0.000	1.140	0.59	1.01
3/11/82E**	2.265	0.575	0.005	1.105	0.54	1.24
5/11/82	2.630	0.592	0.207	1.387	0.84	4.62
			DREDGED MATERIAL ISLAND - DEEP			
6/25/81	2.675	0.674	0.103	1.063	1.24	3.71
8/13/81	3.180	0.826	0.124	0.900	1.09	8.60
11/19/81	2.841	0.794	-0.049	1.004	6.78	28.65
3/11/82	2.710	0.705	0.106	1.190	0.99	5.68
5/11/82	2.700	0.573	0.138	1.348	1.51	2.67
			MIDDLE MARSH EMBAYMENT			
6/25/81	2.924	0.711	0.362	1.272	3.46	10.96
11/19/81	2.882	0.857	0.549	0.945	4.38	27.46
3/11/82	3.073	0.943	0.043	0.960	2.20	19.66
5/11/82	3.008	0.946	0.050	1.058	4.96	18.22
			SHACKLEFORD SHOAL			
6/25/81	2.141	0.694	-0.238	1.169	0.87	0.16
8/13/81	2.299	0.520	0.070	1.292	0.74	1.22
11/19/81	2.368	0.536	0.092	1.529	1.21	2.31
3/11/82	2.323	0.520	-0.067	1.233	1.49	0.86
5/11/82	2.458	0.534	-0.056	1.424	2.06	1.66

* S = samples taken in shoalgrass planting section.

** E = samples taken in eelgrass planting section.

Table 4

Mean Monthly Seawater Temperatures (^{o}C) for All Study Years Referred to in the Text

YEAR		MONTH J	F	M	A	M	J	J	A	S	O	N	D
1978		8.0	5.3	11.6	18.4	21.8	26.2	27.6	29.0	26.4	20.2	17.8	12.8
1979		9.3	6.6	13.2	18.0	21.9	24.1	27.0	27.7	25.3	20.8	17.0	11.7
1980		10.0	6.8	10.8	17.9	21.5	24.7	30.2	28.2	27.4	20.9	15.3	8.8
1981		8.4	9.1	11.6	17.2	20.9	27.1	27.0	26.4	25.2	19.2	14.5	9.2
1982		7.5	10.7	13.3	16.4	22.5	25.6	28.0	27.5				
	$\bar{X}$*	8.6	7.7	12.2	17.5	21.7	25.5	28.0	27.8	26.1	20.3	16.2	10.6
	S.D.	1.0	2.2	1.1	0.8	0.6	1.2	1.3	1.0	1.0	0.8	1.5	1.9

NOTE: Data station is located at Duke Marine Laboratory, within Back Sound, and 13 km from most distant planting site.

* Grand means are presented by month for all years combined.

Table 5

Sediment Flux Rate (SFR) at Planting Sites

Site	SFR* cm/day
Middle Marsh Embayment 1981 eelgrass site	0.000
Shackleford Shoal 1981 shoalgrass site east half, shallow to deep (three sites)	0.017 0.051 0.661
Shackleford Shoal 1981 shoalgrass site west half, shallow to deep (three sites)	0.102 0.186 0.254
Dredged Material Island 1981 shoalgrass site, shallow site	0.017
Shackleford Shoal 1981 shoalgrass site	0.053
Barden Inlet 1981 eelgrass site	0.600

* 50-day coverage.

Table 6

Survival of Planting Units as of October 1982 at Transplant Sites in North Carolina

Location	Species	Date Planted	Percent Surviving
Middle Marsh Embayment	Eelgrass	10/78	72
	Eelgrass	10/81	0
	Shoalgrass	7/81	0
	Shoalgrass	10/78	0
Shackleford Shoal	Eelgrass	10/79	95
	Eelgrass	10/81	95
	Shoalgrass	6/81	36
	Shoalgrass	6/82	81
Dredged Material Island			
shallow	Eelgrass	10/81	56
deep	Eelgrass	10/81	0
	Shoalgrass	6/81	0
Barden Inlet	Shoalgrass	6/81	0
Bigfoot Slough	Eelgrass	7/81	0
	Shoalgrass	7/81	0

Table 7

Reproductive Efforts for Natural (N) and Transplanted (TP) Populations of Eelgrass

Location and Population Type N or TP	Date Planted Month/Year	Date Sampled Month/Year	Number of Shoots Sampled	Flowering Shoots as % of Total
Middle Marsh Embayment (TP)	10/78	5/79	105	13.3
Middle Marsh Embayment (TP)	10/78	5/79	120	13.3
Middle Marsh Embayment (TP)	10/78	5/80	310	26.0
Middle Marsh Embayment (N)	-	4/78	102	32.3
Shackleford Shoal (TP)	10/79	4/80	362	10.5
Shackleford Shoal (TP)	10/79	4/80	494	14.6
Shackleford Shoal (N)	-	4/81	118	30.5
Shackleford Shoal (TP)	10/81	3/82	322	23.8
Middle Marsh Embayment (TP)	10/81	3/82	394	11.2
Dredged Material Island-deep (TP)	10/81	3/82	182	12.5
Dredged Material Island-shallow (TP)	10/81	3/82	207	18.3
Shackleford Shoal (N)	-	3/82	228	37.7
Middle Marsh Embayment (N)	-	4/81	84	25.0
Middle Marsh Embayment (N)	-	3/82	141	13.4

Table 8

Regression Equations for All Experimental Transplant Treatments: Beaufort, N.C.

ln # shoots PU-1	PU^{-1} = slope	X (days)	+	Y-intercept	r	Date planted	Treatment: Stock source	Treatment: Planting Environment	Location: Reference Figure and Letter	Regression: Reference Figure and Letter
Z. marina	= 0.01347	(d)	+	1.9073	0.8183	10/78	HE	LE	1a	3A
	0.01519	(d)	+	1.6907	0.8621	10/78	LE	LE	1a	3B
	0.01806	(d)	-	1.0046	0.8167	NA	Control-Z.m. seedling growth		1a	3C
	0.00751	(d)	+	2.3971	0.7936	10/79	HE	HE	1b	3D
	0.00951	(d)	+	2.2421	0.8449	10/79	LE	HE	1b	3E
	0.00496	(d)	+	2.6256	0.6522	10/81	HE	HE	1a	3F
	0.00589	(d)	+	2.5479	0.6548	10/81	HE	LE	1a	3G
	0.00509	(d)	+	2.2725	0.6422	10/81	HE	LE, shallow end of local distributional range	1c	3H
	-0.00128	(d)	+	2.9275	-0.2010	10/81		LE, deep end of local distributional range	1c	3I
Combined	= 0.00709	(d)	+	2.2431	0.5838	10/81	HE			
H. wrightii	= 0.00596	(d)	+	2.1854	0.6801	6/81	HE,nf	HE,LE	1b	4A
	0.01008		+	2.7820	0.6109	6/82	HE,nf	HE	1b	4B
	0.0	(d)	+	2.3370	0.0	6/81	HE,nf	LE, deep end of local distributional range	1c	4C
	-0.00251	(d)	+	3.4340	-0.1439	6/81	HE,nf	LE	1c	4D
Combined	0.00520	(d)	+	2.5763	0.5789					

HE = high-energy environment (waves and/or currents).
LE = low-energy environment.
nf = planting units assembled with unculled stock; a natural frequency of terminal meristems. This does not apply to Z. marina where all shoots act as terminal meristems that are capable of branching.

Table 9

Recommended Limits for the Major Environmental Factors Identified as Influencing Eelgrass and Shoalgrass Transplants

Environmental factor	Effect(s)	Abbreviated Monitoring Methodology	Duration of Monitoring	Recommended Limits
Temperature and salinity	Temperature: planting season in relation to stress season. Salinity: geographic limit in the estuary.	Thermometer and salinometer or refractometer	Biweekly for at least one lunar cycle before planting.	Temperature: maximize growth time to next stress period. Salinity: above 20 ppt for eelgrass; 20-40 ppt for shoalgrass.
Light-depth interaction	Upper and lower depth limits of transplant survival.	Calculate attenuation coefficients with PAR-measuring instrument or observe depth range of contiguous seagrass population.	Biweekly...	Upper: mean low, low water. Lower: 12.5% of incident PAR avg. during monitoring.
Currents	Site design, logistic problems of planting, PU growth response.	Maximum surface velocity using repeated measures of commercial flowmeter or floating log timings.	Over full tidal cycle at full moon (flood and ebb).	Upper only: 120 cm/sec.
Sediment characteristics	Growth response: especially on new dredged material and chemically polluted sediment.	Monitor containment of dredged material. Suspected chemical pollutants; analyze especially for herbicides by standard methods.	Dredged material: 1 month for suspected chemical pollution. At least 1 sample with replication.	Let dredged material set at least 1 month. Chemical Pollution, no known limits.
Sediment fluctuation	PU survival	Measure absolute change (+/-) in sediment surface height relative to a fixed datum.	50 days before planting.	Less than 0.098 cm/day.

Table 10

Planting Arrangement Data for *Zostera marina* and *Halodule wrightii* on the East Coast of the United States

Expected days to coverage	Y Value (m^2)	
	Halodule wrightii	Zostera marina
100	0.0274	0.0073
125	0.0438	0.0253
150	0.0602	0.0433
175	0.0765	0.0613
200	0.0929	0.0794
225	0.1090	0.0974
250	0.1256*	0.1154

* Out of annual range of growing season north of Florida and on the Florida Keys.

Table 11

Shoalgrass Terminal Shoot Survey

Location and Sampling Time	No. shoots	No. terminals	Percent terminals
Middle Marsh Embayment 7/23/81	195	34	17.4
Harkers Island* 7/24/81	428	132	30.8
Shackleford Shoal 7/23/81	614	90	14.7
Shackleford Shoal 8/5/81			
edge of bed	389	42	10.8
center of bed	442	68	15.4
Shackleford Shoal 6/18/82			
edge of bed	437	83	19.0
center of bed	592	54	9.1

* This is an open-water site with intermediate velocities between the Middle Marsh Embayment and Shackleford Shoal sites.

Table 12

Surface Sediment Samples Taken Inside and Adjacent to Eelgrass Transplant Units

Date	Location	Sediment Parameters* M	So	Sk	Ki	% OM	% S-C
		DREDGED MATERIAL ISLAND (shallow)					
Day 267							
7/2/82	Inside	2.793	0.597	0.082	1.176	0.85	3.49
7/2/82	Outside	2.613	0.585	0.039	1.386	0.84	2.32
		SHACKLEFORD SHOAL					
Day 239							
6/2/82	Inside	2.213	0.552	- 0.136	1.236	1.20	0.56
6/2/82	Outside	2.182	0.555	- 0.105	1.159	1.35	0.68

* Each sample location is an average of at least five randomly sampled replicates at each site. M = mean particle size in phi units, So = sorting, Sk = skewness, Ki = kurtosis, % OM= percent organic matter by combustion and % S-C = percent of sample that is silt-clay size fraction (< 63μ).

Table 13

Sediment Accumulation Data for Three Different Sites Transplanted in Eelgrass

Site	Days Since Planting (t)	Increase in Height(ΔH)* m	Cross-sectional Area at Time t (A_t)** m^2	No. PU Planted per ha	PU Survival Rate Percent	Sediment Accumulated+ m^3/ha
Dredged Material Island (shallow)	236	0.01138	0.1035	10,201	90	10.81
Shackleford Shoal (1981 planting)	234	0.03220	0.0523	10,201	90	15.45
Shackleford Shoal (1979 planting)	423	0.03390	0.2970	10,201	90	92.44

* ΔH = average difference in sediment height inside and outside randomly selected transplant units.

** A_t = average area of transplant units at the given site for that time t .

\+ Sediment accumulated (m^3)/hectare = $\frac{\text{volume of sediment accumulated } (m^3)}{PU}$ x survival rate of PU x PU/ha

where: $\frac{\text{volume of sediment accumulated } (m^3)}{PU} = \Delta H \times A_t$.

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